DEVELOPMENT OF A VERSATILE, LOW COST CERAMIC ARMOR (U)

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ABSTRACT

(U) An SBIR Program is developing and demonstrating the technology necessary to design and fabricate an elastomer encapsulated ceramic tile array using low-cost and high-volume production methods. The armor system utilizes a continuous elastomer encapsulation surrounding ceramic tiles in the array. The elastomer prevents or greatly reduces the damage done to tiles adjacent to impacted tiles by attenuating the lateral stress waves produced. The elastomer also decouples the ceramic tiles from the general, late time response of the target backing. This encapsulated array technology may be employed as the hardface component of structural armor, for parasitic appliqué armor systems, and as armor upgrade to existing vehicles which contain metallic or composite hull/turret structures. Ballistic testing of small tile arrays has enabled the construction of a Second Hit Ballistic Performance Map for an armor system composed of encapsulated ceramic tile array and an aluminum backing plate. This system has been designed to protect against multiple hits of the threat spaced three inches from previous hits. The Map enables optimization of the armor system for a particular application. The permanent deformation of the backing plate after each hit was characterized because control of backing deformation is an important factor in achieving protection against proximate multiple hits. Targets, designed to represent a portion of a full-scale armor, were fabricated as 4 X 4 tile arrays using mass production methods. Ballistic testing of these targets demonstrated their ability to defeat six impacts of the AP projectile at muzzle velocity.

Introduction

(U) Ceramic faced armor systems defeat armor piercing (AP) threat projectiles by breaking up the projectile in the ceramic material and terminating the fragment energy in the backing plate which supports the ceramic tiles. During this process, damage is produced in the armor system. In order for such systems to defeat additional impacts of the threat that are near to previous impacts, the size of the damaged area produced in the armor system needs to be controlled and minimized. With better damage control, the damage size produced is smaller and more closely spaced hits can be defeated by the armor. Armor systems containing segmented ceramics in the form of "tiles" solve a part of this problem because cracks cannot propagate from one tile to another. However, strong stress waves can still damage tiles adjacent to the impacted tile by propagating through the edges of the impacted tile and into adjacent tiles. Ceramic tiles can also be damaged by the deflection and vibration of the backing plate. In addition, impact from the lateral displacement of material during ceramic fracturing can crush and damage adjacent tiles. All of these armor damage mechanisms must be suppressed in order for the armor to possess exceptional multiple hit characteristics.

(U) Stress waves can be effectively attenuated within small distances through the use of viscoelastic materials. A continuous elastomeric material placed around the segmented ceramic tiles very efficiently absorbs the stress waves produced by impact. With proper design, the damage caused by the impact can be limited to the hit tile. The characteristics of this wave propagation are determined by the dynamic impedance, the geometry and the type of the elastomeric material used. The elastomeric material used in this program was chosen based on its density, strength, elongation, toughness, dynamic impedance and time dependent rheology. Unlike metals or ceramics, elastomers (rubbers) can stretch five to ten times their original length and retract fully to their original dimensions when the stress is removed. This behavior is time dependent and strongly affected by temperature and strain rate conditions during the deformation. At low temperatures and/or high strain rates, elastomers display elastic behavior, as in a glassy state. At high temperatures and/or low strain rates, elastomers behave like viscous liquids. The elastomer used in this program exhibited a rubbery characteristic (the transition between glassy and viscous flow states) at strain rates between 10^3 and 10^4 s^{-1}. Designing the armor so that the elastomer deforms in this condition during impact results in maximum shock damping capability.

(U) The major objective of this program is to demonstrate low cost materials, designs, and manufacturing methods for the fabrication of elastomer encapsulated arrays of laterally contained ceramic tiles. Lateral damage should be limited to enable the defeat of proximate multiple hits and the weight/ballistic performance characteristics of the armors are to be optimized. The generic hardface armor component being developed is an integrated package, containing a continuous elastomer phase around segmented, laterally confined ceramic tiles. The elastomer is used to (1) attenuate the shock wave, (2) accommodate the lateral displacement produced by ceramic fracturing, and (3) preserve adjacent tiles during the backing vibration and deformation stage. This type of armor package can be used for stand-alone armors, applique armors, vehicle skirt armors, or the hard-face armor component of other armor systems. Armor systems using this hardface component will be weight efficient for protection against any light to medium AP and fragment threats.

Design of Experiments

(U) Two experimental matrices were undertaken in parallel: Matrix A was a dynamic response study of laboratory-processed, small sized targets, and Matrix B was an evaluation of the multi-hit characteristics of large sized targets fabricated with commercial processes.

Matrix A -Dynamic Response

(U) The objective of this study was to understand the fundamental response of the elastomer-encapsulated ceramic tile array to threat impact. There are many parameters involved with the design of the elastomer-encapsulated armor packages: tile size, spacing between ceramic tiles, elastomer thicknesses, and the areal density of the ceramic tiles and the backing. These experiments investigated the dynamic response of the rubber array for different ceramic tile and backing plate areal densities, and all other design parameters were kept the same. In order to simulate the interaction between hit tiles and adjacent tiles without incurring extraordinary cost in target preparation, armor packages, consisting of 3 X 4 tile arrays, were fabricated with two ceramic tiles and ten surrogate aluminum tiles, as shown in Figure 1. A spall shield was incorporated into the top elastomer layer. Through the mechanism of fiber reinforcement, this spall shield serves to toughen the top elastomer layer which enhances its confinement/containment effects on the impacted tile. The PAD ballistic testing method was employed [1,2]; the areal densities of the targets were varied and all targets were impacted at muzzle velocity. Two impacts were performed, one on each of the two ceramic tiles, to determine the damage created by the first hit and the ability of the armor design to defeat the second hit. Aluminum was selected as the backing material for the ceramic arrays in this program. The deformation characteristics of this backing material are well known. Because of the extensive plastic flow produced in this material without rupture, the final deformation footprint which remains in this material after impact is nearly identical to the maximum dynamic deformation produced during impact.

Matrix B - Multi-hit Capability

(U) Identification of low-cost manufacturing methods is one of the important keys for the success of the program. Hutchinison's expertise in the development and manufacturing of elastomers is playing an important role in the development of designs and fabrication approaches which will minimize the cost of the armor arrays. Hutchinson developed an industrial process to fabricate the armor packages which contained a 4 X 4 ceramic tile array, as shown in Figure 2. A "multi-elastomer" approach was selected in which more than one type of elastomer was used in the encapsulation. The rubber used on the surface of the package has excellent resistance to oil, gasoline, ozone and water swelling. The interior rubber of the package has dynamic properties appropriate for control of the dynamic response of the tiles in the array. After fabrication, the elastomer-encapsulated tile-array was bonded to an Al backing plate. Various hit positions were tested to evaluate the multi-hit capability.

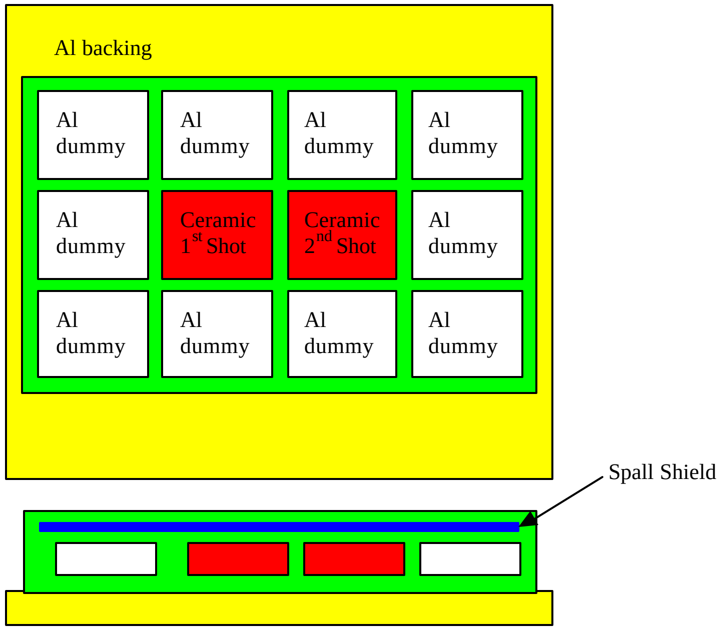


Figure 1. (U) Specimen Configuration for Dynamic Response Study

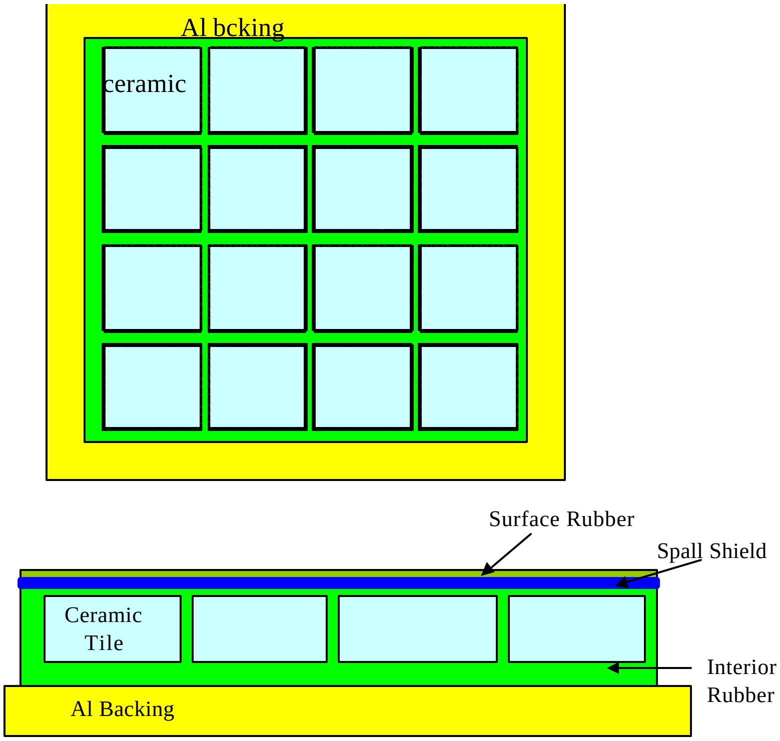


Figure 2. (U) Specimen Configuration for Multi-hit Capability

Results and Discussions

(U) Nineteen small-scaled targets were fabricated and tested to study the dynamic response of the elastomer-encapsulated ceramic-tile arrays. The Protection Areal Density (PAD) curves, for defeating both the first and second shots, were measured as shown in Figure 3. These curves represent a 0.50 probability, with 90% confidence, of defeating the first projectile hit and defeating the second projectile hit spaced 3 inches from the first hit; i.e. Pp(hit1) = 0.5 and Pp(hit2) = 0.5, both at 90% confidence level. There are two main Test Lines for the experiments. The first Test Line employs the same backing areal density (7 lb/ft^2) for all targets and varies the ceramic tile areal density. The second Test Line maintains constant ceramic areal density (13 lb/ft^2). The total areal density required to defeat a single hit is less than the total areal density to defeat two hits which are closely spaced. It is clear that the targets designed for closely spaced multiple hit protection will be heavier than the targets designed for single hit protection. It is noted that the shape of the second shot PAD line is much narrower than the one for the single shot PAD line. This indicates that the design optimization for multi-hit protection is more sensitive to component areal density and more difficult to identify than the optimization for a single hit armor. The minimum weight armor system design is at the minimum point on the curve. If the PAD curve were for a probability of partial penetration, Pp >= 0.9, this system areal density would be adequate for a robust, reliable armor system. In order to demonstrate this, additional ballistic tests are required. The results of such testing might indicate the requirement for a small increase in system areal density to achieve these levels of reliable threat defeat. For armor designs which utilize thin ceramic tiles and thick Al backing (low weight percent ceramic designs), the second hit PAD curve coincides with the first hit PAD curve, indicating a negligible difference between single-hit and two-hit performance in metallic armor systems. This is true; the lateral damage produced in metallic armor systems is typically smaller than that produced in ceramic-faced armor systems. However, metallic armor systems require considerably greater area density to defeat the threat than an optimized ceramic-faced armor system.

(U) Ballistic impact creates significant plastic deformation in the backing plate. The bulge is strongly related to the dynamic response of the armor system. After the first hit, four measurements were made using a counter gage along 0, 45, 90 and -45°, as shown in Figure 4. Both bulge height and bulge diameter at half-height were measured. All targets defeated the first shot. The average bulge height (B_H) and the average bulge diameter at half-height (B_D) are presented in Figure 5. Opened diamonds and squares indicate a complete penetration of the second shot and solid diamond and squares indicate partial penetration of the second shot. It is clear that the ballistic performance against the second shot is strongly dependent upon the backing deformation (backing damage) created by the previous impact. With a constant aluminum backing areal density, the maximum bulge height decreased as the ceramic thickness increased, but the bulge diameter increased as the ceramic thickness increased. Maintaining the same ceramic areal density, both the bulge height and the bulge diameter decreased as the backing thickness increased. These results can be understood by consideration of the deformation mechanics of the aluminum plate, the geometry of the "footprint" of the ceramic conoid, and broken projectile debris which impact the backing plate.

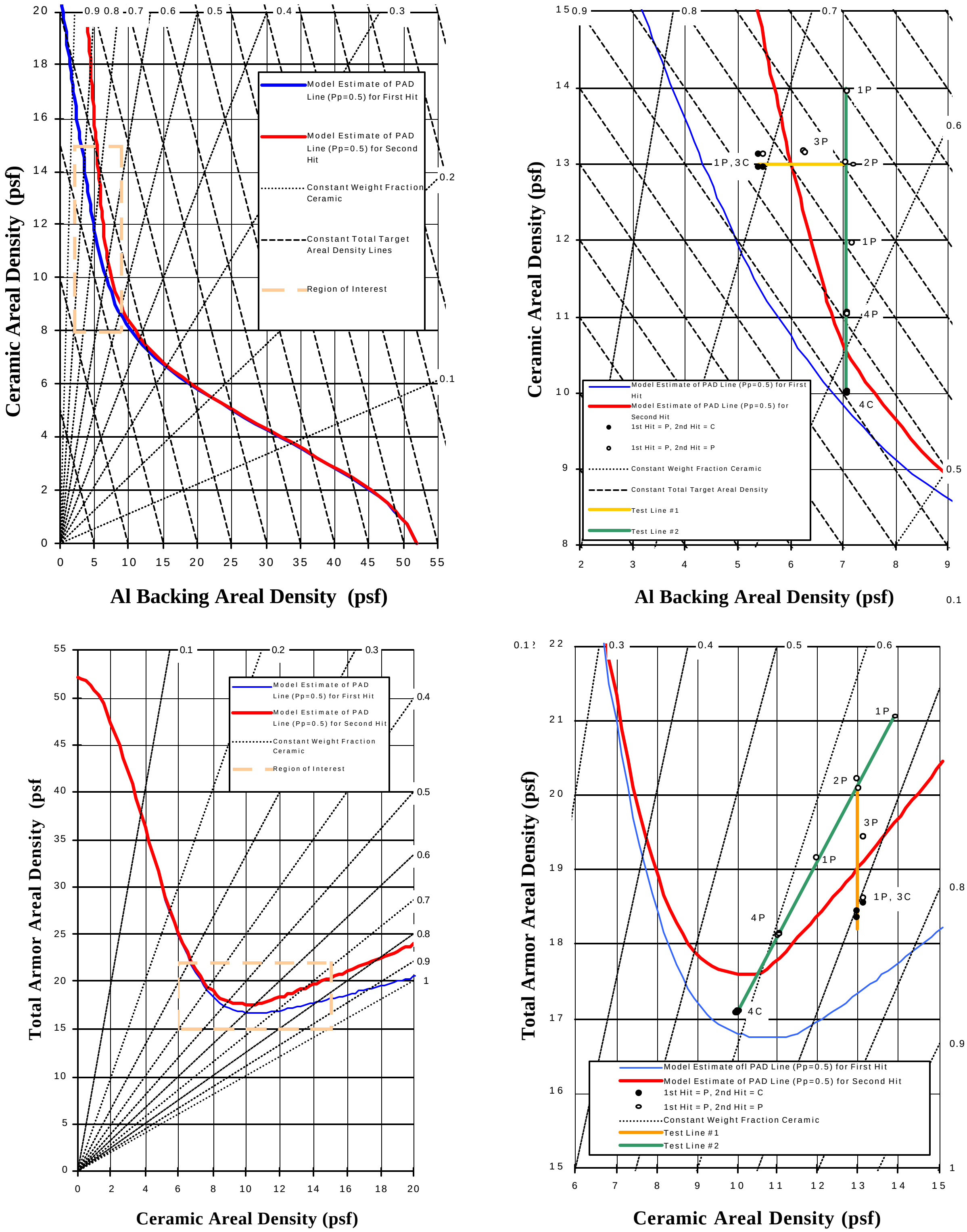
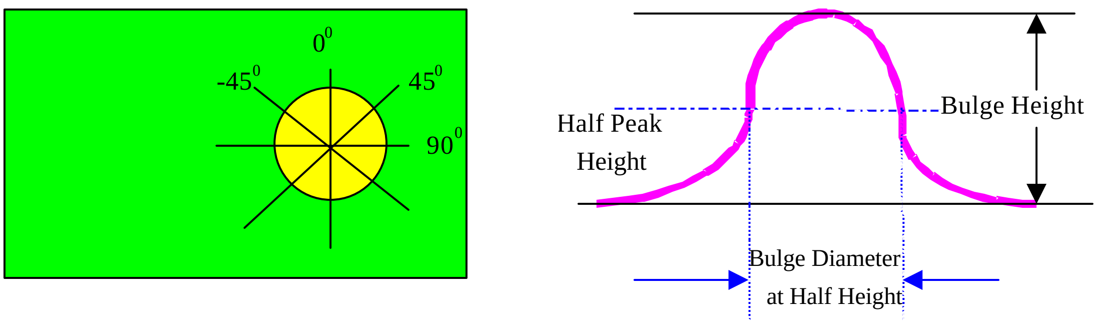
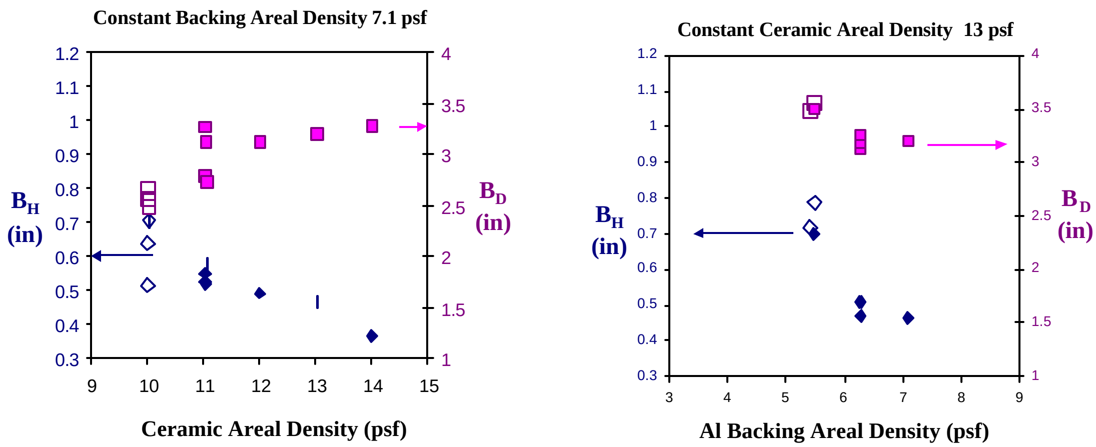


Figure 3. (U) Ballistic Performance Map



(a) (b)

Figure 4. (U) Measurement of aluminum backing bulge after the first shot:
(a) Four Measurements on the backing plate, and
(b) Measurement of Bulge Height and Bulge Diameter at Half Height.



(a) (b)

Figure 5. (U) Average Bulge Height and Average Bulge Diameter at Half-Height
(a) Constant Backing Thickness (7.1 lb/ft^2)
(b) Constant Ceramic Thickness (13 lb/ft^2).

(U) The backing deformation provides important insights into the operative projectile defeat mechanisms [1, 2]. During impact, the projectile is blunted, cracked and shattered by the hard ceramic face. Fragmentation and comminution are produced in the ceramic and the projectile, resulting in fine ceramic rubble travelling with the projectile. Some of the incident momentum of the fast, intact projectile is transferred to shattered projectile and the ceramic rubble. The ceramic rubble typically has a mass comparable to the initial projectile; hence, the final shattered projectile and ceramic rubble exhibit a much lower impact velocity on the backing plate. Because of the conoid formation in the ceramic and the deflection of the broken projectile pieces, the impact force on the backing is distributed over a large area, and the magnitude of the dynamic traction is significantly reduced. The backing plate undergoes a plastic deformation during deceleration, and captures the broken projectile pieces and ceramic rubble. If the incident impact momentum is not effectively transferred to a large mass of ceramic rubble, the Al backing may reach its shear instability, leading to adiabatic shear plugging. When the ceramic areal density is reduced, the ceramic debris mass and footprint area are reduced and the dynamic traction is increased on the backing. As a result, the bulge height is increased, and the bulge diameter is reduced. On the other hand, the change in the backing areal density does not affect either the debris footprint area or the dynamic traction on the backing. With lower backing areal density, less backing material is available for plastic deformation under the debris footprint area and the lower mass backing can be more easily accelerated by the debris impulse. Consequently, the reduction in the backing areal density promotes larger bulge height and larger bulge diameter.

(U) The backing deformation is a critical parameter for the multi-hit performance. The backing deformation behind the impacted tile can extend to the adjacent ceramic tiles. If the deformation induced by the first hit is severe, the adjacent tiles will not have a sufficient structural support to break up the second hit projectile. In metallic backed armor systems, the most important characteristic of the backing deformation is the surface curvature beneath the adjacent tiles; this is the interface damage. If the curvature is large, the adjacent tiles may suffer a bending load during the second hit which renders them much less effective. Since neither the ceramic tile nor the elastomer is transparent, it is very difficult to accurately measure the surface curvature beneath the adjacent tiles before they are impacted with a second hit.

(U) Extensive measurements of the bulges produced in the backing plates were made. Aluminum has a simple deformation; i.e., small elastic deformation and well-characterized, work hardening plastic deformation. The deformation behavior of aluminum is much simpler than the complex viscoelastic deformation and delamination in composite backings, such as Kevlar and Spectra. The final deformation of the Al backing is nearly identical to the maximum dynamic deformation during impact. The thickness of the deformed Al backing plate varies because of the extensive plastic deformation which occurs; the indent on the front plane of the Al plate is different from the bulge on the back plane of the Al plate. Nevertheless, the bulge measurement on the on the back plane of the Al backing plate is still an excellent indication of the interface damage. A hypothetical deformation map is proposed in Figure 6.

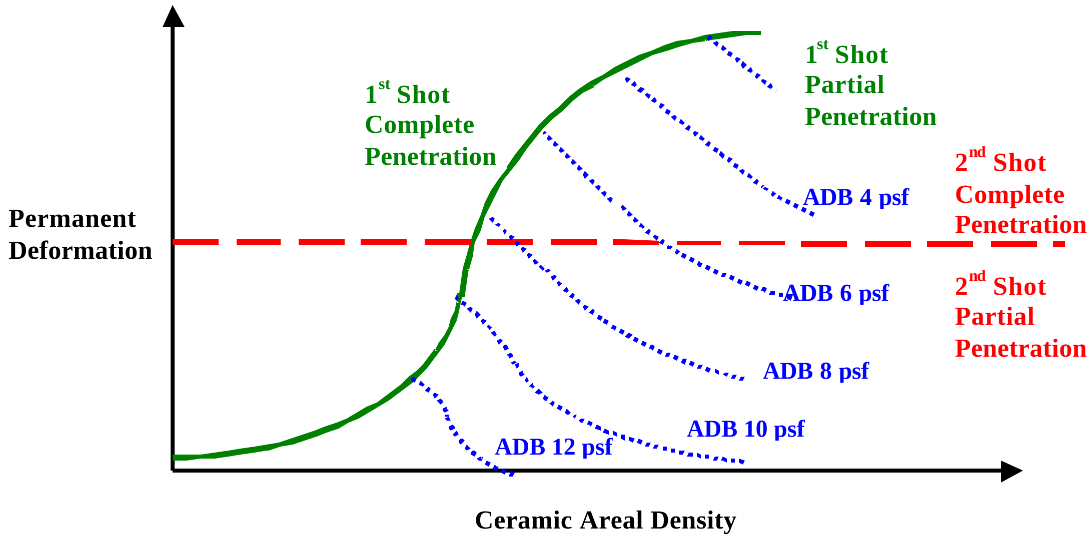


Figure 6. (U) Hypothetical Deformation Map

(U) With the same backing areal density (along the same ADB curve), the permanent deformation in the backing reduces as the ceramic areal density increases, because of the increase in the debris footprint area. With a very large ceramic areal density, the permanent deformation approaches to zero (This occurs when the aluminum plate response is completely elastic.). A similar trend is expected for armor systems with other backing areal densities. However, the deformation curve may be slightly different for armor systems with large backing areal densities. Since localization of the deformation from adiabatic shear is predominant in armor systems containing thin ceramics and thick backing plates, a small increase in ceramic areal density may not reduce the permanent deformation significantly. If the ceramic areal density is sufficiently increased, the extent of shear localization will be reduced and the deformation will decrease significantly. Armor systems containing thin ceramics and thin backings will not defeat the first impact and a curve can be drawn to separate the partial and complete penetration under the first shot. To defeat the second shot, the armor system requires not only sufficient ceramic and backing for defeat of the projectile but also a strong ceramic/backing interface for structural support. An armor system suffering a large permanent deformation from the first shot cannot defeat the second shot and it is expected to have a threshold deformation for defeating the second shot. There is a weight penalty for armor systems designed to defeat multiple hits because the plastic deformation of the backing plate must be controlled. The backing deformation has been investigated in this study and the methodology developed can be applied to armor system designed for more than two hits.

(U) Hutchinson has demonstrated a commercial rubber process to fabricate 12X12" rubber assemblies with multi-elastomer configuration. The surface rubber offers resistance to non-ballistic threats; the internal rubber provides the dynamic response and viscoelastic rheology required for the multi-hit capability. During the testing, the target was bolted onto a steel frame providing the edge support typical of a vehicle application and the impact velocity was fixed Five hits were tested on specimen No. 28, and six hits were tested on specimen No. 29. The hit positions were near to the center of each ceramic tile. All hits exhibited partial penetrations on these two targets. Figure 7 shows the testing sequence, and the front face as well as the back face of the tested targets.

(U) It was noted that both bulge height and bulge diameter were affected by the testing sequence, this occurs because the adjacent ceramic tiles provide lateral confinement to the impacted tile. During the first hit, all four adjacent tiles are intact and the induced confinement is significant. As the testing continues, the lateral confinement from the adjacent tiles becomes less because the later impacted tiles do not have four intact surrounding tiles (some surrounding tiles have already been impacted). As described above, the structural support provided to the tiles by the backing plate is very important for achieving good multiple hit performance. As the multi-hit testing progresses, the structural support is also degraded because of the accumulated backing deformation. The success shown in defeating six shots in the 12X12" area indicates that the encapsulating elastomers have exceptional capability to isolate and preserve the adjacent tiles around the impacted tile. The lateral damage in the ceramic tile array has been successfully controlled through the elastomer encapsulation approach.

Conclusion

(U) To date this program has demonstrated that through the use of proper elastomer encapsulation, ceramic tile arrays can be designed and fabricated that will defeat proximate, multiple impacts of an armor piercing threat projectile. These encapsulated arrays are amenable to fabrication with low cost, commercial production methods and can be tailored for many different applications. A principal factor in achieving excellent multiple hit protection is the control of the damage created in the backing plate by the threat impact. Control of this damage appears to require modest increases in the armor system areal density over that required to defeat only single hits.

References

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Acknowledgement

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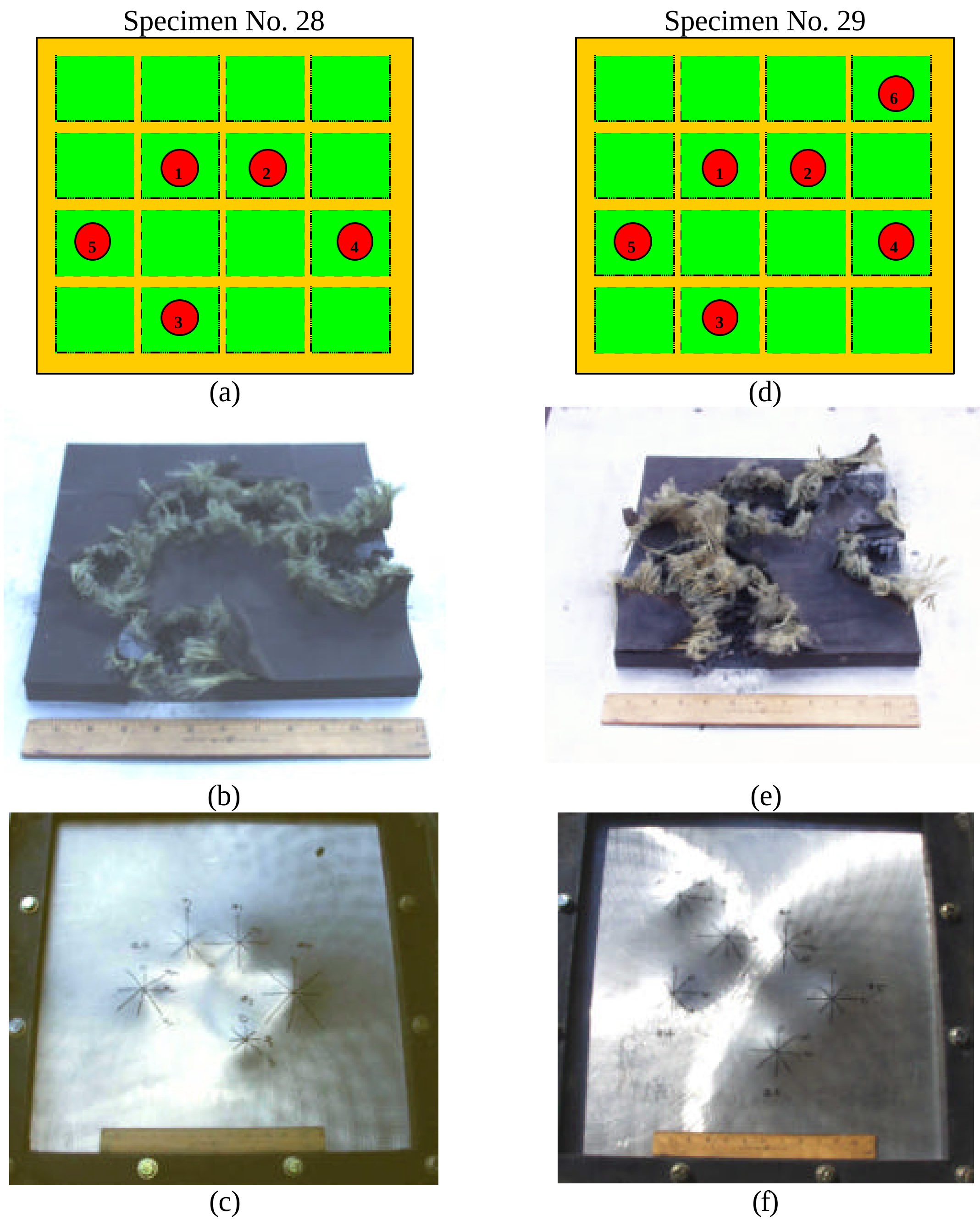

Figure 7. (U) Multi-hit Testing
Specimen No. 28: (a) Test Sequence, (b) Front Face, (c) Back Face
Specimen No. 29: (d) Test Sequence, (e) Front Face, (f) Back Face